ANALYSIS OF CLOUD-TO-GROUND LIGHTNING CLUSTERS WITH RADAR COMPOSITE IMAGERY

THESIS

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Abstract

The horizontal distance that cloud-to-ground lightning travels is an area of research interest for both military and civilian installations. The most recent research conducted at the Air Force Institute of Technology involved studying a large volume of lightning data without coupling radar imagery (Parsons 2000). Parsons finding could not be acted on because no individual storms were studied. The primary goal of this research is to determine whether the techniques used by Parsons can be applied to storms by examining the radar imagery and lightning data. This research used the methodology applied to lightning data by Parsons and radar imagery to determine whether the location of lightning clusters were located near storms. A composite reflectivity radar image was generated and the lightning data for the corresponding time was plotted to determine if lightning clusters corresponded to storm coverage area. After a visual analysis of the radar and lightning cluster plots was conducted, the percentage of lightning clusters found in each radar image was calculated. In general most of the lightning clusters were found along the edges of the composite reflectivity. Caution needs to be applied when calculating the distance to the flashes isolated from nearby clusters since the clusters were found to be near the edge of the storms studied and not under the convective core of the storm. This research was successful in proving that the DBSF method may be applied, however more research must be done to determine what location of the storm provides the best distance criteria measurements.

ANALYSIS OF CLOUD-TO-GROUND LIGHTNING CLUSTERS WITH RADAR COMPOSITE IMAGERY

1. Introduction

1.1 Background

All Air Force and Army installations with active airfields have advisory criteria for lightning. On April 29, 1996, a routine "lightning within 3" advisory was issued at 0804 CDT at Hurlburt Field, Florida after a weather observer spotted a single lightning strike about 3 miles west of the airfield. The base weather station canceled the advisory at 0930 CDT, approximately 90 minutes after the initial lightning strike was observed. At 0938 CDT a fatal lightning flash struck the airfield killing one airman and injuring 10 others (Bauman 1998:slide 6). The fatal flash was estimated to have traveled five to seven miles from storms located south of the airfield by air traffic controllers. Following the fatal incident, the Air Force Safety Agency assembled a Lightning Safety Review Panel to determine if lightning procedures were adequate.

The Air Force Operational Safety and Health (AFOSH) Standard 91-100 states, "A Lightning Watch is in effect 30 minutes prior to thunderstorms being within a 5 nautical mile radius of any pre-determined location or activity as forecast by the Base Weather Station. A Lightning Warning is in effect whenever any lightning is occurring within a 5 nautical mile radius of the pre-determined locations and activities." Lightning Warnings stop all outdoor activities on military installations when lightning is within 5 nautical miles, while Lightning Watches are issued to inform of an approaching storm only. There is no clear explanation as to why 5 nautical miles was chosen as the "safe" distance for lightning warnings by AFOSH. It has been postulated that 5 nautical mile criteria exists as a result of increasing distance response to lightning incidents until a proper balance between threat and impact were achieved (Roeder and Pinder 1998).

Three previous students of the Air Force Institute Technology (AFIT) have done research on the horizontal distance lightning travels. Two students were unable to provide an accurate horizontal distance calculation and only studied a limited amount of lightning data. The most recent research effort involved studying a large quantity of lightning data over the entire United States using the distance between successive flashes (DBSF) method. No individual storms were studied in the most recent research, only lightning data. With the archived data available from the National Lightning Detection Network (NLDN) and from the Weather Surveillance Radar (WSR-88-D), it is now possible to study storm characteristics to determine whether the DBSF method used in the most recent research efforts is used in predicting a safe distance from storms.

1.2 Problem Statement

The primary goal of this research will be to use radar imagery to confirm that the DBSF method is valid when trying to determine the distance lightning travels from storms. Prior studies have proven that there is no "one" safe distance. Studying several storm types and looking at the general trends that are present within the lightning and radar imagery will also provide useful information for anyone interested in this problem. This will aid in the development of an objective criterion for safe operations that balance threat and impact.

2. Literature Review

2.1 Lightning Flash

Lightning is a transient, high-current electric discharge. The path length of a lightning flash is very unpredictable and is on the order of kilometers (Uman 1987). There must be a separation of positive and negative charge regions within a thunderstorm for lightning to be present. While the process of charge separation in convective cells is not fully understood there is on going research in this area and the dipole charge separation theory is widely accepted.

Lightning discharges occur within differently charged regions and are classified according to where the discharge begins and terminates. When a lightning discharge occurs between a cloud and the ground it is referred to as cloud-to-ground (CG) lightning. A lightning discharge occurring between two charged regions of the same cloud is called intracloud lightning, while lightning discharge between two different clouds is called intercloud lightning. Cloud-to-ground lightning accounts for less than half of the lightning discharges, but it is the most widely studied type of lightning (Uman 1987). Cloud-to-ground lightning is widely studied because it poses the greatest threat to life and causes damage to susceptible ground systems. This thesis will focus on cloud-to-ground lightning.

2.1.1 Cloud-to-ground Discharge Process

The CG lightning discharge process has several components. The flash is the total electric discharge and takes less than a second to complete (Uman 1987).

This process is started when there is sufficient charge separation in a convective cloud. When the potential difference between the charge region and atmosphere reaches or exceeds the breakdown potential of the atmosphere a coronal or point discharge is initiated from the charged region into the atmosphere (Uman 1987). The discharge from the cloud is called a leader. Leaders are approximately 50 meters in length and travels approximately 1×10^5 m·s-1 (Idone and Orville 1982). Leaders move outward and downward toward the ground or other clouds.

The entire path of leaders from the cloud to the ground is called a stepped leader. As the stepped leader get close to the ground a breakdown potential at the surface is reached and at this point an upward moving discharge called the attachment leader travels from the ground to the leader (Uman 1987). An electrical circuit is completed when the attachment leader and stepped leader connect and a path is formed from the cloud to the ground. Next, in the process is the transfer of charge to the earth with a return stoke travelling from the ground upward. The return stroke travels at approximately 2×10^8 $m \cdot s^{-1}$ (Idone and Orville 1982). After the return stroke, which is the brightest part of the flash, additional discharges from the charged region may take place following previously ionized paths. This additional discharge is called a dart leader and travels approximately 3×10^6 m·s-1 (Uman 1987). With each dart leader, another return stroke is initiated. The number of return strokes in a flash is called the multiplicity. Figure 1 illustrates the cloud-to-ground lightning process.

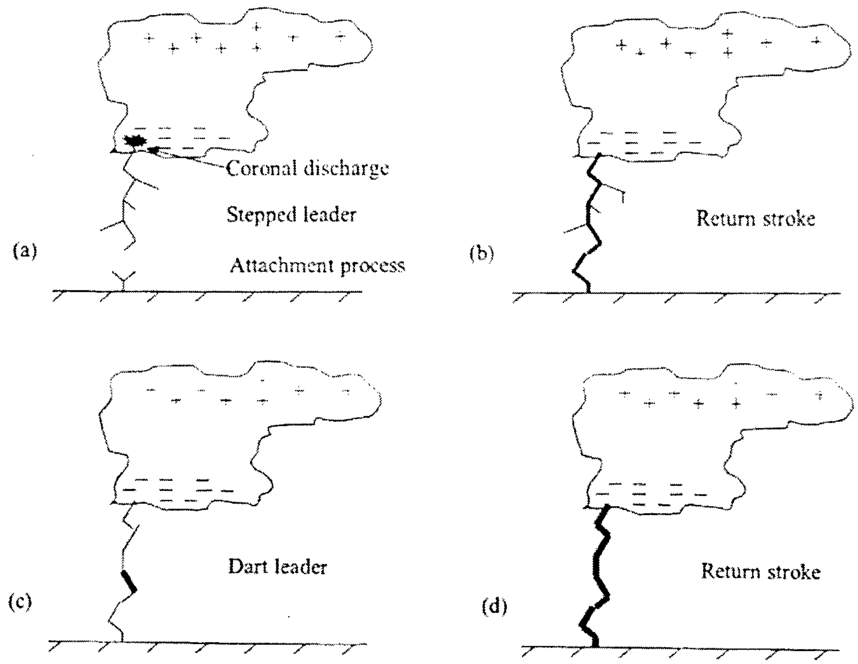

Figure 1. Cloud-to-ground lightning process. a) Coronal discharge happens at the negative charge region followed by the stepped leader which propagates away from the cloud. As the charge approaches the ground the attachment process occurs and there is an upward discharge of charge. b) As the discharge occurs the return stroke returns the charge back into the cloud region. c) Process is complete by dart leader returning the charge back down the cloud and the final d)return stroke occurs. (after Uman 1989)

2.1.2 Categorization of Cloud-to-Ground Lightning

Four different types of CG lightning have been identified and are illustrated in Figure 2 (Uman and Krider 1989). Negative CG flashes probably account for about 90% of the CG discharges worldwide, and less than 10% of the lightning discharges are initiated by a downward moving positive leader. Ground to cloud discharges are initiated by leaders that move upward from the ground. These upward initiated flashes are rare and usually occur near mountains and tall man-made structures.

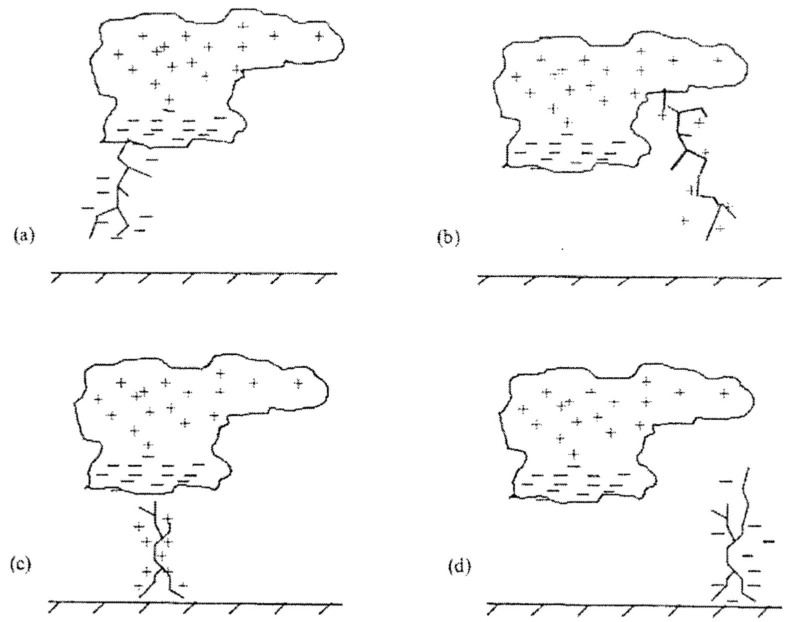

Figure 2. Categorization of CG lightning flashes. a) Negative cloud-to-ground flash. b) Positive cloud-to-ground flash. c) Positive ground-to-cloud flash. d) Negative cloud-to-ground flash. (after Uman and Krider 1989)

2.2 National Lightning Detection Network

The National Lightning Detection Network (NLDN) began in 1987 when three independent networks were combined to form one national network (Cummins et al. 1998). Since 1989, Global Atmospherics, Inc. has operated and controlled the NLDN. The NLDN provides real time lightning information on a national scale. In 1994, the NLDN was upgraded due to growing commercial demands. The upgrade involved combining Magnetic Detection Finders (MDF) and Time of Arrival (TOA) detection methods into one sensor called IMProved Accuracy from Combined Technology

(IMPACT) (Cummins et al. 1998). The NLDN consists of 59 TOA sensors and 47 IMPACT sensors. Figure 3 shows NLDN sensor locations.

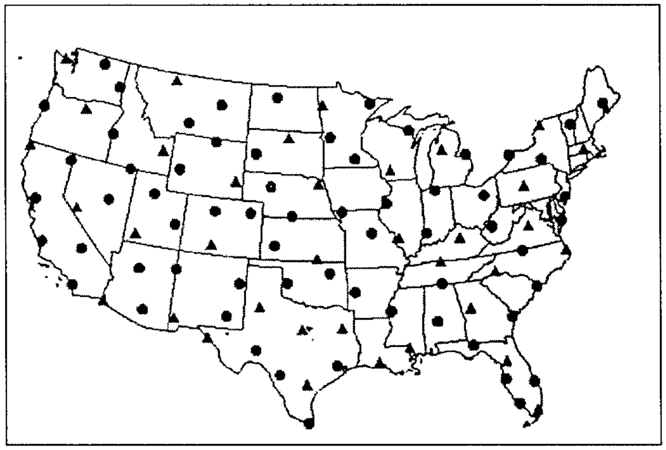

Figure 3. NLDN sensor locations. Triangle are TOA sensors while circles are IMPACT sensors.

The 1984 upgrade improved location accuracy, the percentage of lightning discharges detected and long term reliability of the NLDN. Location accuracy of the NLDN increased from about 2.5 km to 0.5 km (Cummins et al. 1998). Detection efficiency also improved from between 65% - 80% to 80%-90% from first stroke with a peak current of 5 kA or larger (Cummins et al. 1998). Idone et al. (1998) conducted an evaluation over the northeastern U. S. during and following the upgrade and found that there was a modest increase in the detection efficiency of the NLDN.

2.3 Distance Between Successive Flash Method

The distance between successive flash (DBSF) method is one way to determine the distribution of CG lightning flash distances between individual flashes and lightning cluster centers. This method uses temporal and spatial data to cluster lightning flashes into groups. Krider (1988) used a variation of this method to group lightning data for a study of three thunderstorms near Cape Canaveral, Florida. Lopez and Holle (1999) used this method to conduct research on the distribution of DBSFs for different types of storms in four parts of the country. Parsons (2000) also used this method to study the distribution of lightning over the entire U.S. Lopez and Holle's (1999) methodology will be described along with a discussion of how Parsons (2000) modified the DBSF method.

Lopez and Holle (1999) used the following methodology. First a time-ordered data set of lightning flashes from the NLDN database is obtained. Next, the algorithm takes the first flash in the data set and selects a successive flash that is not separated from the first one by more than 15 km or 5 minutes. Then, once the successive flash is found, the next flash is determined in the same way. A series of consecutive flashes constitutes a cluster of flashes. The search for the next successive flash within a cluster ends when a flash is found in the ordered data set that occurred more than 5 minutes after the last flash assigned to the cluster or no flash is found within 15 km. Flashes that are not within the time or distance criteria are identified as outliers. These outliers are used in other clusters if they meet the time or distance criteria. Eventually, all flashes are part of a cluster or identified as isolated flashes.

2.3.1 Modified Distance Between Successive Flash Method

Parsons (2000) used the DBSF method also but with some modifications. Initially, Parsons used 12 minutes as the time criteria and distance criteria of 17 km. With the 12 minutes time criteria and 17 km distance criteria between 18% and 30 % of all flashes were isolated of single flash clusters. One of the goals of Parsons research was to reduce the number of isolated or single flash clusters. In order to reduce isolated flashes, Parsons increased the time criteria to 15 minutes. The same programs used by Parsons will be used in this thesis to determine if the clustering methods used may be applied to storms by examining the radar imagery and lightning data.

2.4 Weather Surveillance Radar 1988 Doppler (WSR-88D) Background

2.4.1 System Overview

The WSR-88D is a product of the Next Generation Radar Program (NEXRAD) and was developed jointly by the Department of Commerce, the Department of Defense, and the Department of Transportation. There are approximately 150 operational sites in the Continental United States that are operated by the U.S. Air Force and the National Weather Service. The WSR-88D network provides nearly complete coverage within the continental U.S. Network coverage at 10,000 feet above site level is nearly continuous with the exception of the western U.S.

The WSR-88D collects, processes, and displays high resolution and high-accuracy reflectivity, mean radial velocity, and spectrum width data. From these basic doppler quantities, computer-processed algorithms generate a suite of meteorological and hydrological analysis products. The WSR-88D system has three major functional components: Radar Data Acquisition (RDA), Radar Product Generator (RPG), and Principal User Processor (PUP).

The radar data acquisition units acquire and process Doppler weather radar data. The RDA consists of the antenna, pedestal, radome, tower, klystron transmitter, receiver, minicomputer and signal processor. The RDA's status and control processor controls antenna scanning patterns, signal processing, ground clutter suppressor, status monitoring, error detection, automatic calibration, and the capability to record the base data. The base data from the RDA, which can recorded as Level II data, is output in digital format by the signal processor along with system status information to properly interpret data (Crum et al. 1993). Information from the RDA is passed on to the radar product generator.

The radar product generator does a majority of the data processing. It executes algorithms to convert RDA-generated base data into meteorological and hydrological products. The RPG also provides dealiasing, control and status monitoring of the RDA and RPG, algorithm output, and product distribution. Data from the RPG is recorded as Level II data. The RPG passes products to the principal user processor. The principal user processor consists of a minicomputer, system console, applications console, color printer, graphics processor, workstation, and communication system. The PUP displays, annotates, manipulates, and distributes products. It also controls and monitors PUP system status and records products.

2.4.2 WSR-88D Operations

The WSR-88D has an effective range of 460 kilometers for reflectivity measurements and 230 kilometers for velocity and spectrum width measurements. WSR-88D algorithms have been designed to process data appropriate for resolutions consistent with spatial scales or relevant meteorological phenomena. Figure 4 illustrates effective ranges at which the WSR-88D data are received and meteorological algorithms are active.

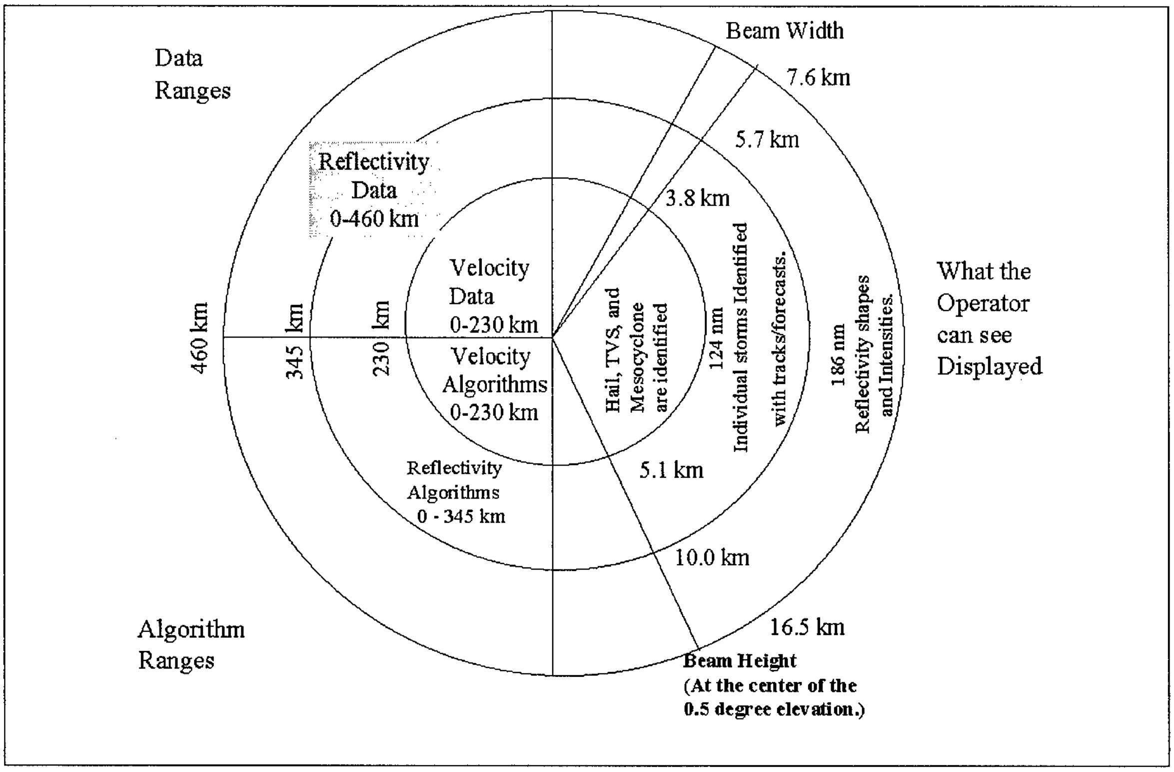

Figure 4. Ranges at which WSR-88D data are received and meteorological algorithms are active. (Adapted from Crum and Alberty 1993)

The WSR-88D antennas continually scan their environment in a sequence of preprogrammed 360-degree azimuthal sweeps at various elevation angles. One complete sequence of azimuthal sweeps is called a volume scan. There are two operational scan modes used by the WSR-88D. These modes are referred to as clear air mode (mode B) or precipitation mode (mode A). The two modes contain two volume coverage patterns (VCPs) with the number of elevation scans per volume being determined by the VCP. The precipitation mode has two VCPs, VCP 11 and VCP 21. VCP 11 consists of 14 elevation angles and is completed in about 5 minutes. VCP 21 consists of 9 elevation angles and is completed in about 6 minutes. Clear Air Mode is used when precipitation echoes are not in range of the radar. The coverage patterns in mode B are VCP 31 and VCP 32. Table 1 shows the WSR-88D volume scan strategies.

Table 1. WSR-88D volume scan strategies, number of 360 sweeps, number of elevation angles, and time per scan strategy.

Scan Strategy	**Volume Coverage Pattern**	**Number of 360 azimuthal sweeps**	**Number of azimuthal sweep angles**	**Elevation range of azimuthal sweeps**	**Time to complete (minutes)**
Clear air (short pulse)	31	7	5	0.5 to 4.5	10
Clear air (long pulse)	32	8	5	0.5 to 4.5	10
Precipitation	21	11	9	0.5 to 19.5	6
Severe weather	11	16	14	0.5 to 19.5	5

2.4.3 WSR-88D Level II data

Level II data is digitally based data that is output from the RDA's signal processor in polar format. This data is the same data transferred from the RDA to the RPG. Table 2 provides the spatial and data resolution of the WSR-88D Level II data.

Table 2. Spatial and data resolution of WSR-88D Level II data. (adapted from Crum et al. 1993)

Doppler moment	Spatial resolution	Data resolution
Reflectivity	95 by 1 km	0.5 dBZ
Radial velocity	0.95 by 0.25 km	0.5 ms^{-1}
Spectrum width	0.95 by 0.25 k	0.5 ms^{-1}

Level II data includes reflectivity, mean radial velocity, spectrum width data, and the system status information that is required to properly interpret the data. The system status information required to properly interpret data includes RDA data status, maintenance performance data, RDA to RPG console messages, maintenance log data, RDA control command, clutter bypass maps and antenna scanning patterns. All RDA's have a slot for a Level II data recorder. Level II data can be played back through the RDA at the same rate the data was collected. Currently, Level II data is recorded on reusable 8-mm tapes. Each tape can hold approximately 4.7 gigabytes (GB) of data. Table 3 show the data flow rate for Level II data and approximate time it takes to fill a tape at different scan strategies.

Table 3. WSR-88D Level II data flow rates and approximate time to fill a 4.7 GB 8-mm tape

Scan Strategy	Approximate MB hr^{-1}	Approximate number of recording hours per 4.7 GB tape
Clear air	44	107
Precipitation	101	46
Severe weather	177	26

Level II data is archived at the National Climatic Data Center (NCDC) and can be obtained for research purposes. Level II data is processed by a program known as WSR-88D Algorithm Testing and Display System (WATADS).

2.5 WSR- 88D Algorithm Testing and Display System

The WSR-88D Algorithm Testing and Display System is a product of the National Severe Storm Laboratory (NSSL) and consists of many special meteorological computer programs other wise known as algorithms. WATADS was created for scientific operations officers within the NWS, NEXRAD agencies, and universities to conduct studies of the meteorological algorithms and the study of severe weather events. WATADS was designated to run on Hewlett Packard and Sun Unix workstations using the X-windowing system.

WATADS reads archived Level II data from the WSR-88D that has been stored on 8-mm data tapes. This data is then processed with algorithms developed by NSSL and the algorithms used by the WSR-88D system. WATADS provides for point and click adjustments of both WSR-88D and NSSL adaptable parameters (WATADS 1998).

The display portion of WATADS is called the Radar Analysis and Display System (RADS). RADS was designed for visualizing WSR-88D data processed by WATADS. RADS allows the meteorologist to analyze radar data and meteorological algorithm output in great detail. RADS display products such as base reflectivity, composite reflectivity, spectrum width, vertically integrated liquid, base velocity, and precipitation accumulation.

WATADS data are organized according to volume scan number since the WSR-88D processes and archives data by volume scan. All WATADS algorithms process data by volume scan number rather than specific times and all products, data, and other information are updated by the RDAs data server process only when the volume number changes.

As noted in the WATADS reference guide (WATADS 1998), WATADS generates many large data files for base data images, derived images, product overlays, and other information. The suggested amount of disk space per volume scan of radar data is at least 8 megabytes. Data processing occurs at a rate comparable or slower than the rate at which the event occurred in real time. Despite this limitation, WATADS is a valuable tool for studying case studies, algorithm performance verification, individual algorithms, and comparing baseline and NSSL enhanced algorithms.

3. Methodology

3.1 Objectives

The primary goal of this research is to determine if the modified DBSF method used in previous research can be applied to storms by examining the radar imagery and lightning data. A secondary goal of this research is to determine what factors can aid in the improvement of the lightning clustering method previously used. A third goal of this research is to look at the various characteristic lightning clusters have when applied to different storm types.

3.2 Scope

Processing Level II data using WATADS requires over 8 megabytes of disk space per radar volume scan analyzed. Analyzing one day worth of Level II data typically takes about one day to process using WATADS. The amount of data that one can process is limited since processing Level II data requires large volumes of computer memory and considerable time constraints.

All Level II data used in this research was ordered from the Air Force Combat Climatology Center. All lightning data was on hand at AFIT. Lightning data used for this thesis came from 1996, 1998, and 1999.

The locations used in this thesis were limited to five sites. Sites were chosen based on their distance from military installations. Table 4 provides a list of the locations used in this research.

Table 4. WSR-88D sites chosen for this research.

LOCATION	ID	LATITUDE (°N)	LONGITUDE (°W)
Eglin AFB, FL	KEVX	30.56	85.92
Flagstaff, AZ	KFSX	34.57	111.20
Melbourne, FL	KMLB	28.11	80.65
Oklahoma City, OK	KTLX	35.33	97.28
Raleigh, NC	KRAX	35.67	78.49

The locations chosen for analysis were randomly selected based on the number of lightning flashes for a given 24 hour period. Initially a program was used to determine which days had an adequate number of CG lightning flashes. Only the months of March to November between 1995 and 1999 were considered for all lightning data this was the same period examined by Parsons. No winter storms were analyzed in previous research either. The aim of the research was to get several regions that had different type of thunderstorms. Previous researchers have limited the type of storms studied so that more adequate result could be obtained.

3.3 WSR-88D Algorithm Testing and Display Procedure

Once all data tapes from the five locations to be studied were ordered they needed to be processed with WATADS. Extracting the information on the Level II data tapes using WATADS involves several steps. First a WATADS directory must be set up. The WATADS directory is where all radar files for each site will be stored. Next, one must select the adaptable parameters to be used and set to desired levels, and select setting which algorithms will be executed. Since this research only involved looking at reflectivity composites for overall relationship to lightning clusters the adaptable parameters and algorithm settings were not altered.

Prior to the data tapes being processed sounding information must be input before any algorithms will be executed. The 12Z sounding information for the particular day being processed was used in all cases. Table 5 provides a list of the dates, times, and locations used for the level II data tapes along with times and total lightning flash count from each location.

Table 5. Date, time and total lightning flashes used at each radar location

Location	Date	Time	Total Lightning Flashes
Raleigh, NC	April 4, 1998	2247-2340	43
Eglin AFB, FL	July 6-7, 1996	2050-0004	1056
Flagstaff, AZ	September 14, 1996	1034-1150	1576
Oklahoma City, OK	July, 10, 1999	0105-0215	6028
Melbourne, FL	August 13, 1996	2022-2341	3054

According to page 2-16 of the WATADS Version 10.0 Reference Guide, wind speed and direction must be entered for at least one sounding level for velocity dealiasing algorithms. Calm winds could have been entered and no information would have been lost but in order to get better storm track information, the 12 Z soundings were used.

WATADS allows the user to index the tape so that only a certain portion, or a specific range of volume scans and time on a Level II data tape can be processed. After the WATADS directories were set up, the adaptable parameters set, the desired algorithms selected, sounding data entered, and the volume scans selected, the Level II tape was ready for processing. As mentioned before the processing time can be long for these data tapes. The length of processing time depends on how many volume scans were selected to process, the VCP that the radar was in when recording the data, and the number of thunderstorms within the radar image.

Once all of the Level II data tapes were processed, RADS was used to review the composite reflectivity of the radar imagery to be used with lightning cluster plots. The composite reflectivity was chosen so that most of the regions of precipitation could be detected. Composite reflectivity provides a better estimate of where precipitable cloud coverage is located than the base reflectivity product since altitude is not a factor. Another benefit of using the composite reflectivity is to match the time interval of the images with the sorted lightning data. It takes approximately six minutes for the composite reflectivity to go through all elevation angles and complete one volume scan. When two of the images are merged together there will be approximately 10 to 12 minutes worth of data to plot on an image. Figure 5 provides an example of how composite reflectivity scans are constructed.

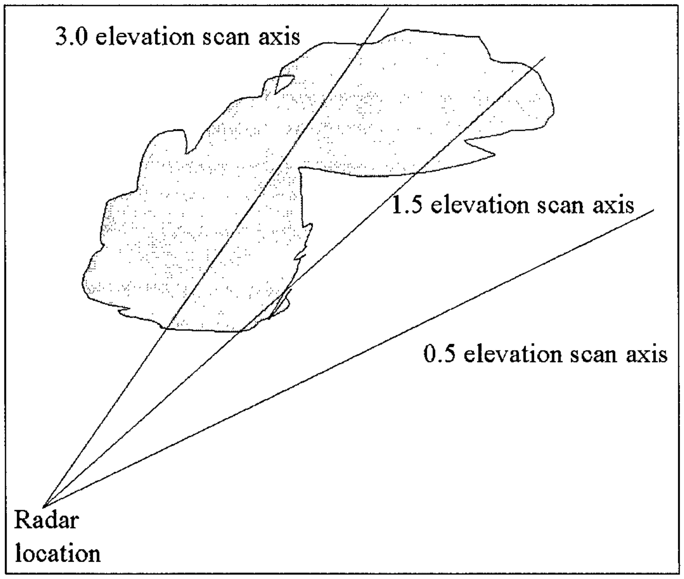

Figure 5. Composite Reflectivity Example. At the 0.5 elevation scan axis no reflectivity value is being recorded. The next highest elevation angle is examined to determine whether any reflectivity values are found. The 0.5 elevation scan reflectivity would be combined with the next highest elevation scan reflectivity values and the highest reflectivity values are recorded for the composite reflectivity scan.

3.4 WSR-88D Imagery with Lightning Cluster Procedure

Once all of the Level II data was processed and ready for reading, each image had to be individually saved. Like processing the Level II data the methodology used for saving the radar images was also time consuming. WATADS does not provide a way to save images in a simple manner, instead all images must be captured in a region snapshot and saved to file. There were 121 images saved for use in this thesis. The initial image saved from each location had a polar grid map overlay that would be used to convert the pixel locations on each image to latitude and longitude values.

There were three programs written in the Interactive Data Language (IDL) that were used to process radar imagery along with previous programs used by Parsons (2000) to cluster lightning data. The first program, radarmap, was used to map the location of two points on the images with polar grid overlays. This program only had to be run once for each location. First the calibration image was opened and displayed. Next the center latitude and longitude for the radar site was entered. Then two points along the grid were selected at known distances in nautical miles along with the angle of each point. All information was saved to an output file for later use. The output file contained the following: latitude, longitude, first point location, first point distance, first point angle, second point location, second point distance, second point angle, image bottom location.

The second program that was run converted the pixel information for the data image to latitude and longitude values. This program read in the output file from the radarmap program. All distances were converted from nautical miles to kilometers. The location for the two points previous selected where converted to latitude and longitude values. These values where then used to find the pixel to degree conversion. A region was then defined for the lower left corner latitude and longitude and upper right corner of the image. This would be used later to keep image size consistent when lightning was plotted onto the radar composite. The next step used in the second program was to convert colors to reflectivity values. Finally, another output file was generated to save the region information, number of pixel in the x direction, number of pixels in the y direction, and pixel degree conversion. The output file generated a text file that could be used to contour the images onto maps of the different locations.

The third program was used to read in image files and lightning data for contouring and plotting. Initially, two images where selected and merged together to form a time composite ranging between 10 and 12 minutes depending on which VCP the radar was operating in at the time of the scan. By merging two images the time more closely matched that of the lightning algorithm which used a time of 12-15 minutes. Next the two images were contoured and all reflectivity values greater than 18 decibels (dBZ) were color filled. The reasoning for choosing 18 dBZ is because this is the reflectivity value at which precipitation typically reaches the ground or can be classified as rainfall.

All lightning data was sorted with the same programs used previously by Parsons (2000). The lightning output files where then read into the third program so that only flashes from the time of the radar image would be plotted in the contoured region. Some lightning clusters where divided between several images because all of the lightning information was grouped based on the entire time span. A text file was then generated that contained the cluster number and total number of flashes plotted in the reflectivity portion of the image for each cluster along with the minimum and maximum distances from reflectivity for each flash within a cluster. The percentage of flashes from each cluster found inside the reflectivity region was calculated and is provided in Appendix A-E. All images where then saved as GIF images. A sample image will be provided in Chapter 4.

4. Result and Analysis

4.1 General Characteristics of Data

This section discusses the general characteristics found in all data images and lightning cluster information. A visual analysis was done of all imagery after the radar images were contoured and the lightning flashes were plotted over the contouring. Examples of the general characteristics discussed within this section can be found in the sample data analysis section of the individual radar locations.

One thing initially noted was a lag of lightning flashes behind the direction of storm motion. There was some separation in the reflectivity and lightning clusters in some locations. Melbourne had a significant number of flashes that were visible outliers for one of its time periods with no reflectivity in the area.

Parsons(2000) DBSF method limited the number of isolated flashes in a region by grouping the isolated flashes with its nearest cluster. There were only a few isolated flashes for each of the locations studied. Table 6 provides the percentage of isolated flashes at each of the five locations.

Table 6. Percentage of isolated flashes at each radar site

Location	Total Lightning Flashes	% of Isolated Flashes
Raleigh, NC	43	6.98%
Eglin AFB, FL	1056	2.17%
Flagstaff, AZ	1576	1.71%
Oklahoma City, OK	6028	0.25%
Melbourne, FL	3054	0.95%

Note that the percentage of isolated flashes for each location is directly related to the amount of flashes within the region. As the number of flashes increases there is a decrease in the percentage of isolated flashes.

The next step in the analysis process was to investigate the percentage of each lightning cluster found in the reflectivity region of each image. The lightning clusters that had some percentage of flashes within the reflectivity or cloud region of the image were not examined in detail. A more detailed analysis was done on the lightning clusters that had no flashes inside the reflectivity region of the image. Isolated flashes were also studied to see if there was any significance in these flashes. An explanation of how all data was analyzed will be provided in the next section.

4.2 Sample Data Analysis

4.2.1 Oklahoma City Analysis

The Oklahoma City area had severe thunderstorms with outflow boundary that were moving to the southeast toward the radar location. There were eight radar composite contour images with lightning cluster plots for the region. As noted in Table 6, there were not a significant amount of isolated flashes for any of the regions studied and Oklahoma City had the lowest percentage of isolated flashes.

One of the first things examined was the number of isolated flashes found within the Oklahoma region since isolated flashes usually pose the greatest threat in storms. There were only four images with isolated flashes for the Oklahoma City region. There were over 6,000 flashes in the region for the time period studied with only eleven isolated flashes for the entire region. The range of the isolated flashes from the reflectivity region, or what will be referred to as the cloud region of the image, was from 146 km to 242 km. These values are very large and are not acceptable values for the scope of this research. When the lightning data is discussed more information will be provided for what might be the possible problem with the range of values.

The next step was to look at the lightning cluster regions for the percentage of flashes outside the cloud region. For the Oklahoma region, a high percentage of clustered flashes were inside the cloud region. Figure 6 provides the radar composite with lightning cluster plots for Oklahoma City. Table 7 shows the statistical information for lightning data found in Figure 6.

Figure 6 and Table 5 will be discussed in further detail to provide a better explanation of how the analysis of the imagery and lightning cluster data was done. One thing that may be noted on imagery without reflectivity close to the radar center is a circular region that does not seem to belong in the image. This circular region is caused by ground clutter that is near the radar site. Tall buildings and trees in the vicinity of the radar cause ground clutter since the radar is only 20 m above the ground.

Three regions have been labeled in Figure 6. Regions A and B represent clusters that are partially inside the reflectivity region. Region A is made of at least three separate clustered lightning regions with the northern most cluster being the region that is outside the reflectivity region. There are significantly more flashes outside of the cloud in region B than in region A. Region C provides an example of isolated flashes that are within the reflectivity region of the radar imagery. Note how the portion of the clusters that are outside of the cloud region within Figure 6 are behind the direction of the separate storms relative motion which is southeasterly.

Radar Composite Contour with Lightning Plot
Oklahoma City, Oklahoma
July 10,1999
0105UTC –0110 UTC

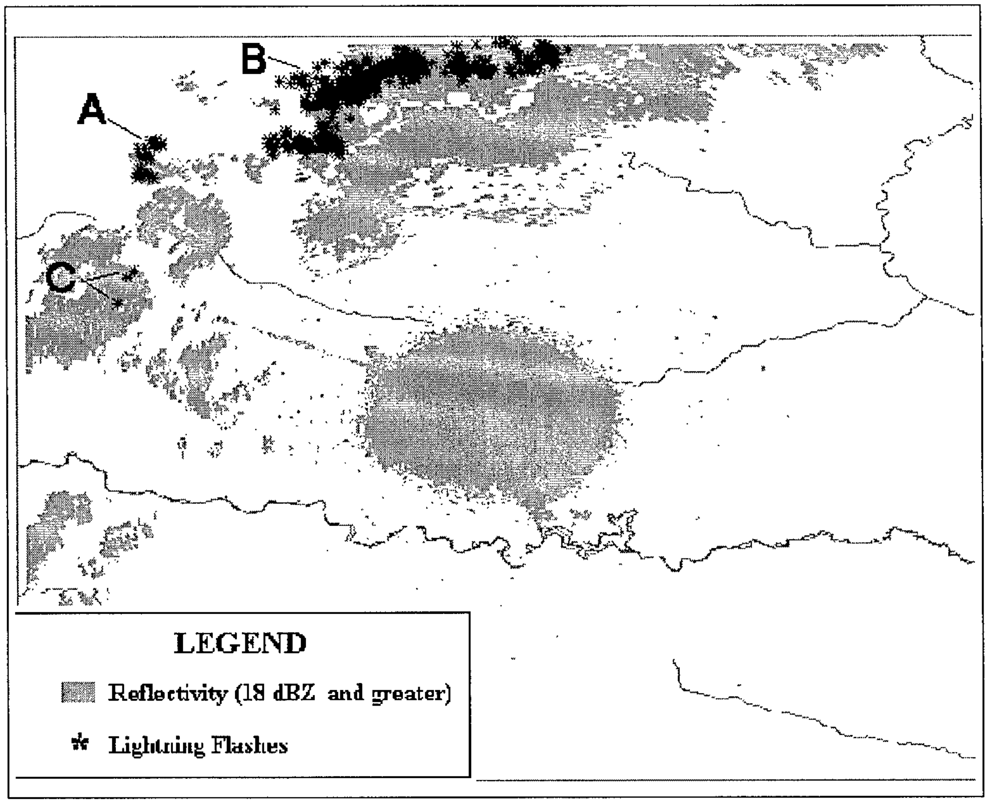

Figure 6. Radar Composite Contour with Lightning Plot for Oklahoma City, Oklahoma. July 10, 1999 0105UTC -0110 UTC. Lightning cluster plots are from 0100 UTC to 0110 UTC. The circular contour near the center of the image should be ignored.

Table 7. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0100-0110 UTC. Image times: 0105-0110 UTC Oklahoma. Flashes defined as in cloud are those with reflectivity values greater than 18 dBZ contoured beneath them on the image.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Minimum Distance From Cloud (km)	Maximum Distance From Cloud (km)
1	277	92.42	0.00	223.31
2	130	100.00	0.00	0.00
3	49	97.96	0.00	145.34
4	86	93.02	0.00	218.18
5	59	91.53	0.00	198.99
6	46	89.13	0.00	217.26
7	21	76.19	0.00	199.34
8	43	97.67	0.00	143.60
9	23	100.00	0.00	0.00
10	12	100.00	0.00	0.00
11	14	92.86	0.00	188.44
12	9	100.00	0.00	0.00
13	4	50.00	0.00	220.48
14	22	54.55	0.00	243.67
15	7	100.00	0.00	0.00
16	5	100.00	0.00	0.00
17	2	50.00	0.00	177.77
18	3	33.33	0.00	191.57
19	5	100.00	0.00	0.00
20	3	100.00	0.00	0.00
21	1	100.00	0.00	0.00
22	2	100.00	0.00	0.00
23	1	100.00	0.00	0.00
24	2	50.00	0.00	191.62
25	1	100.00	0.00	0.00
26	1	100.00	0.00	0.00

The portion of flashes from the cluster that are outside the cloud provide the highest threat when considering the danger lightning poses. Figure 6 does not have any lightning flashes that are not associated with a clustered region and the only information that can be concluded from Table 7 is that there is a range in maximum distance from the cloud region of 143.60 km to 243.67 km. Because the values are so large for the nearest cloud distances to flashes it is highly probable that errors were made in calculating these values. The values for minimum or maximum distances will not be included in the tabular information for the remaining four locations. Excluding the minimum and maximum distance information does not hinder the data analysis because the main goal of this thesis can still be meet without such information. The percentage of flashes inside the cloud region provides very valuable information for the remaining location.

All values for the minimum distance from the cloud region within Table 7 are zero because there were not any isolated lightning flashes or total cluster outside the cloud region of the image. The only case in which there will be a value in the minimum distance from the cloud column of data is in two cases. The first case is when there are isolated flashes in a image. The second case is when there are isolated clusters in a image.

The average percentage of partial clusters in cloud is 42.82 percent. This value was calculated by taking the percentage of flashes in cloud for each cluster that was not entirely inside the reflectivity value summing and dividing by the total number of partial cluster for the region. The average percentage of partial cluster value listed above offers those interested in determining if the DBSF method is valid a better tool for establishing whether the method is or is not acceptable.

4.2.2 Melbourne Analysis.

Another area that provided interesting information was Melbourne, Florida. There were a significant amount of visible outliers on several images from the Melbourne region. Though there were significant outliers on some images others had little to no outliers as seen in Figure 7.

Radar Composite Contour with Lightning Plot
Melbourne, Florida
August 13, 1996
2311UTC –2316 UTC

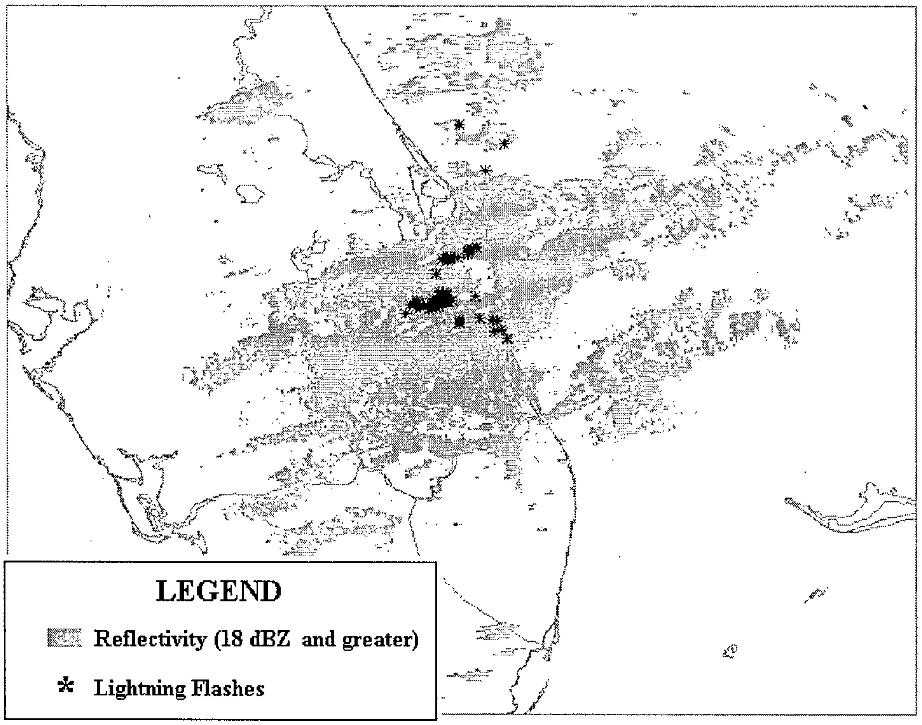

Figure 7. Radar Composite Contour with Lightning Plot. Melbourne , Florida August 13, 1996 2151-2156 UTC. Lightning plot time: 2147-2156 UTC.

The weather scenario for the Melbourne region basically was isolated thunderstorms that developed as a result of a sea breeze. The areas with isolated clusters of outliers for Melbourne can be seen in Figure 8. The area of isolated clusters is labeled in Figure 8 as region A and B. Region A more than likely represents a single cluster, while region B could be two clusters that are close together. The area of isolated clustered outliers has no reflectivity in or around it and is not a region where previous storms had traveled. One might guess that there is possibly a storm in the distance that is generating flashes in this region. The reflectivity to the south of the flashes may be causing the flashes or an error may have occurred with the plotting of the lightning data over the reflectivity. The clusters are approximately 10 km from the nearest reflectivity regions in both region A and B. There are some isolated flashes in the vicinity of the isolated clusters. There are two isolated flashes and 3 clusters with only two flashes per cluster that could be the unexplained flashes in the vicinity of the two main cluster regions. Since only the ground strike locations are recorded, it is impossible to determine if the flashes in region B are from a nearby cloud or if the locations were in error.

Radar Composite Contour with Lightning Plot
Melbourne, Florida
August 13, 1996
2311UTC –2316 UTC

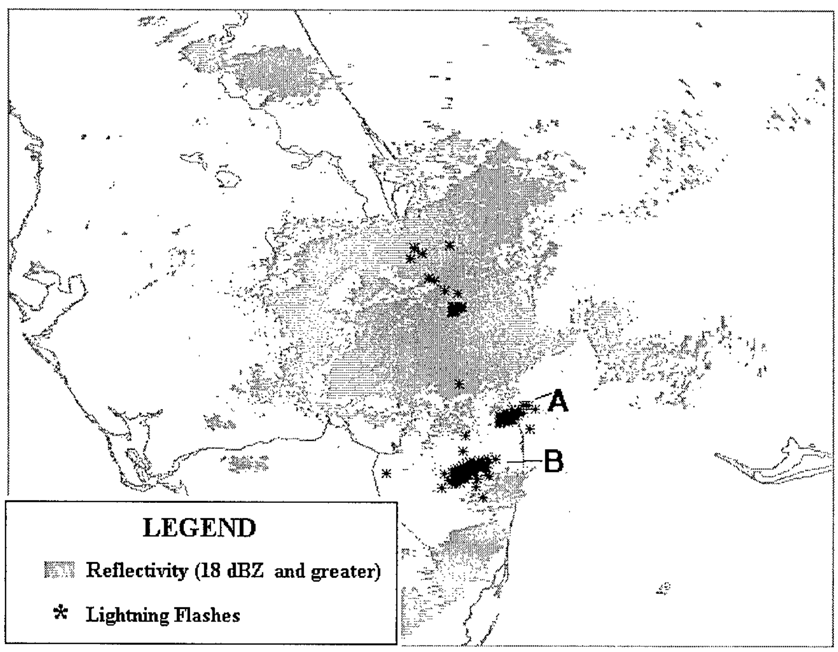

Figure 8. Radar Composite Contour with Lightning Plot. Melbourne , Florida August 13, 1996 2311-2316 UTC. Lightning plot time: 2307-2316 UTC.

The statistical information for Figure 8 is found in Table 8. A visual analysis of Figure 8 would suggest that a low percentage of flashes are in the reflectivity region of the image. By summing the values for the percentage of flashes in cloud found in Table 8 and dividing by the number of clusters the percentage of flashes in the cloud can be calculated. There were only 33.58 percent of flashes found within the cloud region of the image. The average percentage of partial clusters in the reflectivity region was 17.74 percent. These percentages differs from that of Oklahoma City and might suggest that severe storms with high flashes count produce a higher percentage of in cloud flashes than the typical isolated thunderstorm.

Table 8. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2307-2316 UTC. Image times: 2311-2316 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
142	14	0.00	154	42	0.00
143	40	2.50	155	2	0.00
145	7	14.29	156	2	50.00
146	4	100.00	158	1	100.00
147	26	0.00	159	24	4.17
148	13	100.00	160	1	0.00
149	1	0.00	162	2	0.00
151	2	100.00	163	2	0.00
152	3	100.00			

4.2.3 Raleigh Analysis

The data from Raleigh was also examined in order to get an idea of how representative the data from Oklahoma was with the remaining data. There were five radar composites for Raleigh. Raleigh had the least amount of flashes of all regions studied. The thunderstorms in this region were products of a cold frontal boundary overrunning warm moist air. There were only 43 flashes for the entire time period examined.

The average percentage of partial clusters in the reflectivity region was 66.67 percent. There were 88.9 percent of flashes in the reflectivity region of the image. Figure 9 provides the radar imagery for the values that were given above. The flashes within Figure 9 are behind the path of the storm motion. There are only 10 flashes in the image and one may doubt that more than eight of the flashes are within the cloud region. There are small areas of reflectivity located in the region of some of the flashes although not very strong. The Raleigh data agrees well with the Oklahoma City data. Both had approximately 88 percentage of flashes within the cloud region. There were also greater than 50 percent of partial clusters found inside the cloud region of the image.

Radar Composite Contour with Lightning Plot
Raleigh, North Carolina
April 1, 1998
2247UTC -2253 UTC

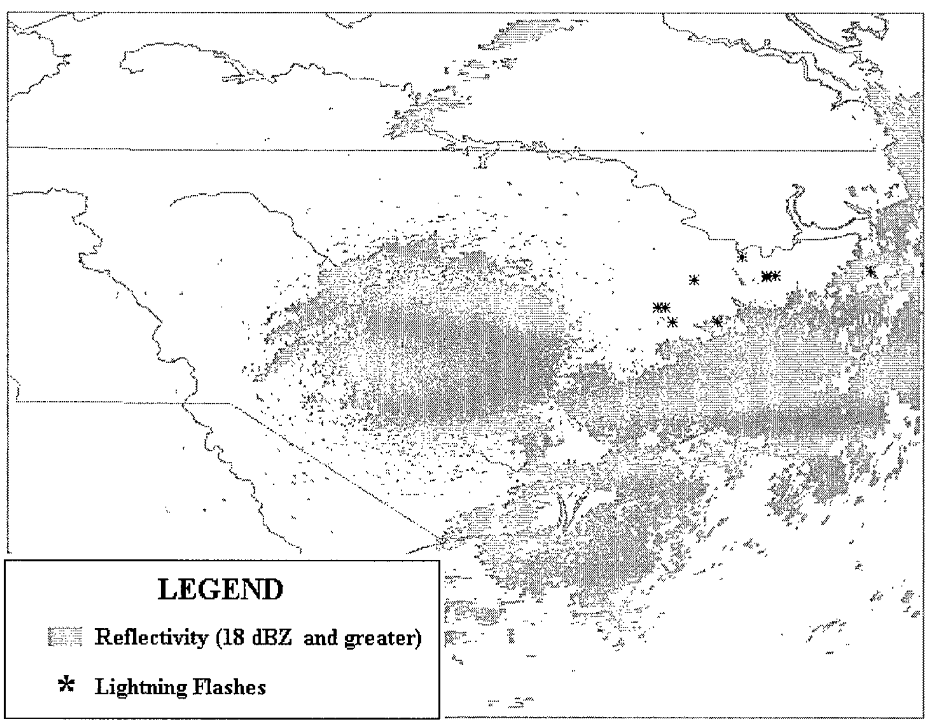

Figure 9. Radar Composite Contour with Lightning Plot Raleigh, North Carolina April 1, 1998 2247 UTC -2253 UTC. Lightning plot times are 2241 UTC –2253 UTC.

Table 9. Lightning Cluster Statistics for Raleigh North Carolina April 1, 1998 2241-2253 UTC. Image times: 2247-2253 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	1	0.00
2	3	66.67
3	1	0.00
4	3	100.00
5	1	0.00
6	1	100.00

4.2.4 Eglin Analysis

The thunderstorms in the Eglin region originate just inland and move southeast toward the Gulf of Mexico. There were 17 radar images analyzed for the Eglin region. Eglin had 21 isolated flashes coming from 12 of the images for the region. While there were 33 clusters that were outside of the reflectivity region in 11 images.

Figure 10 and Table 10 provide the radar imagery and statistical data for one of Eglin's radar images and will be analyzed for similarities with the lightning information from other radar locations examined previously. Labels have been placed on the radar image to identify some areas of clustering (A) along with several isolated flashes (B).

Statistical information was calculated after examining the radar image. The percentage of flashes in the reflectivity region was 59.98 percent for this image and the percentage of partial clusters found in the cloud region was 42.82 percent. While the values for the flashes in the reflectivity region was lower than values found for Raleigh and Oklahoma City having close to 60 percent of the flashes underneath the cloud region.

Radar Composite Contour with Lightning Plot
Eglin AFB, Florida
July 6, 1996
2050UTC -2056UTC

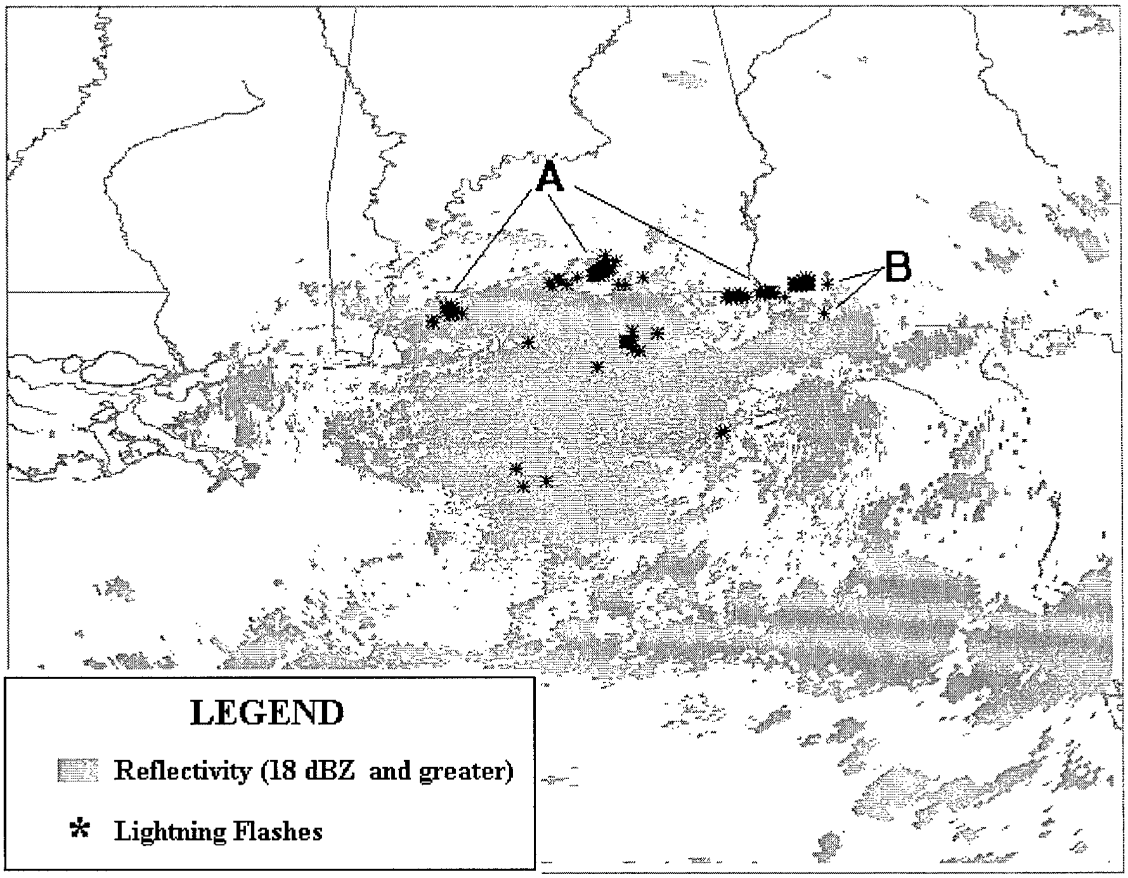

Figure 10. Radar Composite Contour with Lightning Plot Eglin AFB, Florida July 6, 1996 2050UTC -2056UTC. Lightning plot times are 2044 UTC –2056 UTC.

Table 10. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2044-2056 UTC. Image times: 2050-2056 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	56	53.57	11	1	0.00
2	42	9.52	12	3	100.00
3	12	91.67	13	1	100.00
4	12	8.33	14	1	100.00
5	10	20.00	15	1	0.00
6	11	100.00	16	1	100.00
7	1	0.00	17	1	100.00
8	6	83.33	18	1	0.00
9	2	100.00	19	3	33.33
10	1	100.00	20	1	100.00

4.2.5 Flagstaff Analysis

The weather pattern in the Flagstaff radar region consisted of isolated thunderstorms that encircled most of the radar region. There were a high amount of clusters along the western side of the radar image that were not underneath the radar region, once again illustrating the lag of lightning flashes behind the relative motion of storms. This can be seen in Figure 11 in the region labeled A. The accompanying lightning information for Figure 11 can be found in Table 11.

Within Figure 11 for the Flagstaff region there were approximately 61 percent of the flashes that were in cloud, while there were about 67 percent of the clustered regions in area of reflectivity. This information matches up well with the other radar location values with the acceptance of Melbourne. However within region A of Figure 11 there is a similar cluster pattern to that of the Melbourne radar site for those clusters not found inside the cloud region. Like Melbourne, Flagstaff also had regions during this time period with little to no isolated flashes as seen in Figure 12. This may suggest that the DBSF method works the same within regions that have similar synoptic patterns or storms that behave in similar ways.

Radar Composite Contour with Lightning Plot
Flagstaff, Arizona
September 14, 1996
1034UTC -1040UTC

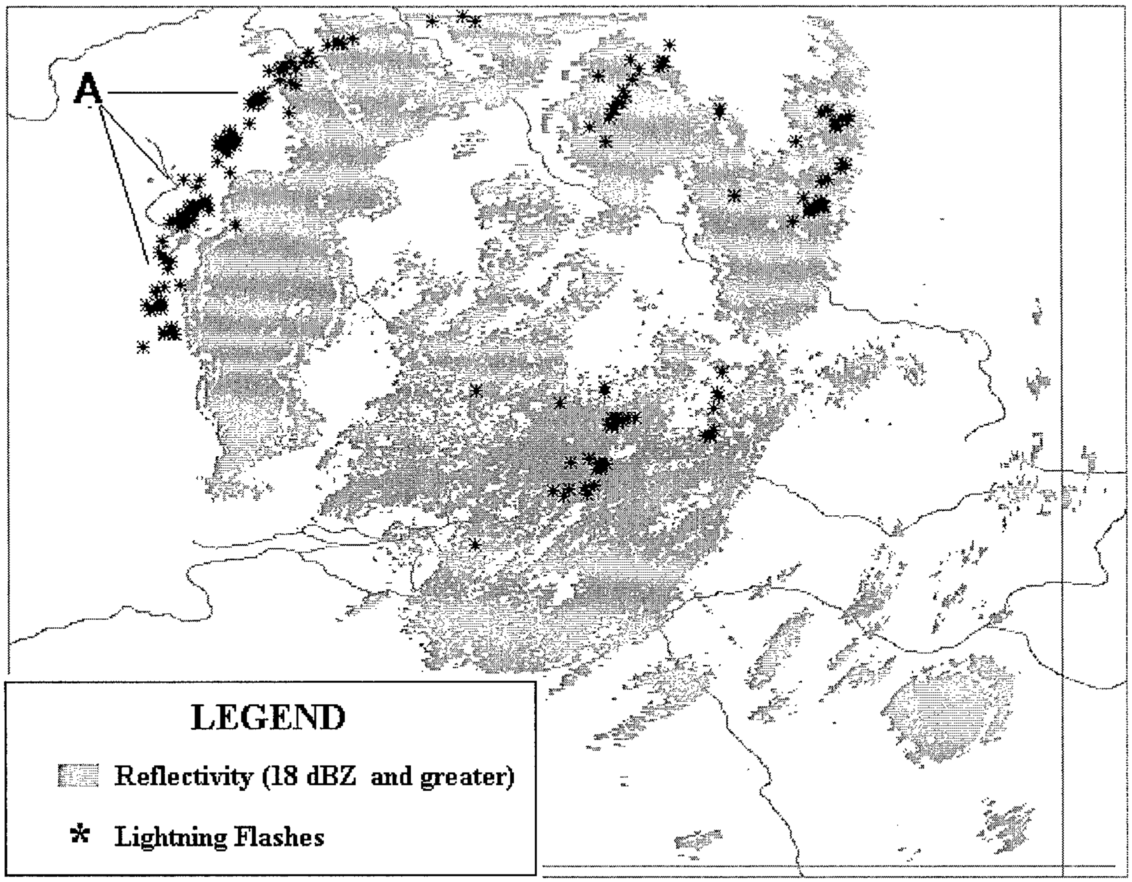

Figure 11. Radar Composite Contour with Lightning Plot. Flagstaff, Arizona September 14, 1996 1034UTC -1040UTC. Lightning plot times are 1028 UTC –1040 UTC

Radar Composite Contour with Lightning Plot
Flagstaff, Arizona
September 14, 1996
1109UTC -1115UTC

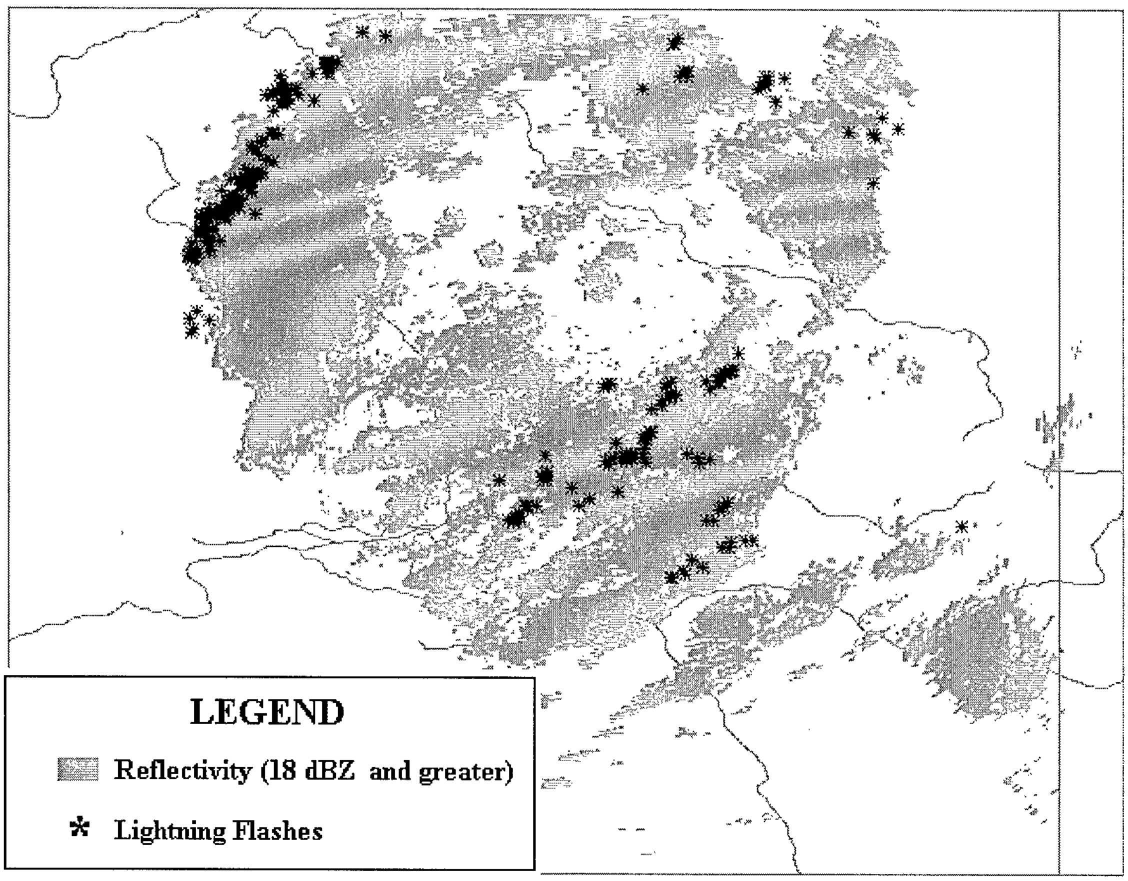

Figure 12. Radar Composite Contour with Lightning Plot. Flagstaff, Arizona September 14, 1996 1109UTC –1115 0UTC. Lightning plot times are 1104 UTC –1115 UTC.

Table 11. Lightning Cluster Statistics for Flagstaff, Arizona. September 14, 1996 1028-1040 UTC. Image times: 1034-1040 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	3	66.67	17	11	81.82
2	11	81.82	19	1	0.00
3	9	100.00	20	1	100.00
4	15	0.00	21	3	66.67
5	15	0.00	22	3	0.00
6	26	0.00	23	1	100.00
7	10	100.00	24	11	90.91
8	6	0.00	25	1	100.00
9	28	39.29	26	2	0.00
10	3	0.00	27	1	100.00
11	7	71.43	28	1	100.00
12	2	50.00	29	2	50.00
13	9	88.89	30	4	75.00
14	4	100.00	32	1	100.00
15	14	100.00	66	1	100.00
16	5	40.00			

5. Conclusions

5.1 Conclusions

Lightning is a very dangerous and unpredictable phenomenon that kills close to 100 people annually. It is very important to be able to predict where it is safe from lightning strikes. Since it is nearly impossible to predict where lightning will strike it is important to develop techniques for estimating the distance lightning travels. Several researchers have already concluded that there is not a specific distance that lightning travels from a storm. An effort was made in this research to test the clustering methods previously used without radar imagery and prove that the lightning clusters could be coupled with radar imagery and determine if the clusters were collocated with the cloud region.

The locations of lightning clusters were found using the DBSF method and plotted on composite reflectivity images. The lightning clusters were examined to determine what percentage of the cluster was in a reflectivity region and the maximum distance from the reflectivity region was calculated. The maximum distance information that was calculated for each region had an error within the algorithm and were deleted from all information in Appendix A-E.

Most of the lightning clusters were located along the trailing edges of area of precipitation areas. While there was a high percentage of lightning within the clusters that fell within the reflectivity region on most images, some images had little to no lightning close to the center of the contoured reflectivity. There were some images that had lightning flashes near the center but overall this was not the trend.

Since the methodology used to cluster the lightning data was developed to limit the number of isolated flashes there were few isolated cases found within the data studied. There was a large amount of variability in the maximum distance that lightning was from reflectivity regions with there being an approximate value of 100 km or greater for most regions. As explained in Chapter 5 the distance values calculated are not correct and have been removed from all data except for the Oklahoma City case.

The DBSF method handles the clustering of data well within most images studied for this research. Melbourne and Flagstaff had areas where a considerable amount of clustered flashes were not inside reflectivity regions during certain phases of storm development. Other areas such as Oklahoma City and Eglin only had a small portion of clustered lightning outside the reflectivity region. The DBSF method when examined with radar imagery provides a valuable tool because it shows certain trends that suggest the need to study the edges of storms not the center. The information that was obtain from using the DBSF method with radar imagery has enough merit to consider the methodology a success when examined to determine if cluster regions pertain to specific storms.

5.2 Future Research Recommendations

There still needs to be continued research into the distance lightning travels. Research could be conducted to find out why there seems to be a lag in the lightning data even when the storm parameters are different. This same area might be examined but only in one location so that a general overview of the synoptic pattern for that area might be studied and general lighting trends may be applied to the various synoptic pattern.

Another area that could be studied is how to better cluster the data. One way to do this may be found if the time constraints within the lightning algorithm are allowed to change with the time of each radar imagery. The distance criteria of lightning clusters and radar images may be researched to find the distance covered by reflectivity to see if there is any correlation between the two.

Appendix A: Lightning Statistics for Raleigh, NC.

Appendix A contains lightning cluster statistics for Raleigh, North Carolina for April 1, 1998 from 2241-2340 UTC. The lightning cluster statistics are for five radar images that occur over the following time period: 2247-2340 UTC.

Table A-1. Lightning Cluster Statistics for Raleigh North Carolina April 1, 1998 2241-2253 UTC. Image times: 2247-2253 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	1	0.00
2	3	66.67
3	1	0.00
4	3	100.00
5	1	0.00
6	1	100.00

Table A-2. Lightning Cluster Statistics for Raleigh North Carolina April 1, 1998 2254-2305 UTC. Image times: 2259-2305 UTC.

Cluster Number	# of Flashes in Cluster	%of Flashes in Cloud
4	1	0.00
6	6	16.67
7	2	0.00

Table A-3. Lightning Cluster Statistics for Raleigh North Carolina April 1, 1998 2306-2317 UTC. Image times: 2311-2317 UTC.

Cluster Number	# of Flashes in Cluster	%of Flashes in Cloud
8.00	2.00	0.00
9.00	10.00	10.00

Table A-4. Lightning Cluster Statistics for Raleigh North Carolina April 1, 1998 2318-2328 UTC. Image times: 2322-2328 UTC.

Cluster Number	# of Flashes in Cluster	%of Flashes in Cloud
10	6	16.67

Table A-5. Lightning Cluster Statistics for Raleigh North Carolina April 1, 1998 2329-2340 UTC. Image times: 2334-2340 UTC.

Cluster Number	# of Flashes in Cluster	%of Flashes in Cloud
10	1	100.00
11	1	100.00
12	2	50.00
13	2	0.00

Appendix B: Lightning Statistics for Flagstaff, AZ .

Appendix B contains lightning cluster statistics for Flagstaff, Arizona for September 14, 1996 from 1034-1150 UTC. The lightning cluster statistics are for seven radar images that occur over the following time period: 1028-1150 UTC.

Table B-1. Lightning Cluster Statistics for Flagstaff, Arizona. September 14, 1996 1028-1040 UTC. Image times: 1034-1040 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	3	66.67	17	11	81.82
2	11	81.82	19	1	0.00
3	9	100.00	20	1	100.00
4	15	0.00	21	3	66.67
5	15	0.00	22	3	0.00
6	26	0.00	23	1	100.00
7	10	100.00	24	11	90.91
8	6	0.00	25	1	100.00
9	28	39.29	26	2	0.00
10	3	0.00	27	1	100.00
11	7	71.43	28	1	100.00
12	2	50.00	29	2	50.00
13	9	88.89	30	4	75.00
14	4	100.00	32	1	100.00
15	14	100.00	66	1	100.00
16	5	40.00			

Table B-2. Lightning Cluster Statistics for Flagstaff, Arizona. September 14, 1996 1041-1051 UTC. Image times: 1046-1051 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
15	1	100.00	42	23	4.35
17	1	100.00	43	1	0.00
19	1	100.00	44	1	0.00
21	2	100.00	45	1	100.00
22	7	0.00	46	1	100.00
23	8	0.00	47	5	0.00
24	1	100.00	48	2	100.00
26	16	0.00	49	1	100.00
27	6	100.00	50	3	66.67
28	1	0.00	51	3	100.00
32	9	0.00	52	3	66.67
33	19	94.74	53	6	83.33
34	2	100.00	54	5	80.00
35	9	100.00	55	1	0.00
36	1	100.00	56	1	0.00
37	8	100.00	57	2	100.00
38	22	18.18	58	1	0.00
39	15	33.33	59	1	0.00
40	2	100.00	60	1	0.00
41	12	58.33			

Table B-3. Lightning Cluster Statistics for Flagstaff, Arizona. September 14, 1996 1052-1103 UTC. Image times: 1057-1103 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
32	2	100.00	63	3	100.00
33	2	100.00	64	7	85.71
34	1	100.00	65	20	100.00
35	1	100.00	66	10	100.00
36	3	100.00	67	2	100.00
37	2	100.00	68	14	92.86
38	11	100.00	69	16	75.00
39	12	83.33	70	5	100.00
41	4	100.00	71	1	100.00
42	4	100.00	72	1	100.00
43	5	80.00	73	2	100.00
44	5	100.00	74	1	100.00
45	3	100.00	75	1	100.00
47	6	100.00	76	6	83.33
48	7	100.00	77	1	100.00
50	2	100.00	78	10	80.00
51	3	100.00	79	2	100.00
52	5	100.00	80	1	100.00
53	9	88.89	81	2	100.00
54	2	100.00	82	5	100.00
55	2	100.00	83	2	100.00
56	3	100.00	84	1	100.00
57	3	100.00	85	1	100.00
58	2	100.00	86	2	100.00
60	2	100.00	87	1	100.00
61	5	100.00	88	1	100.00
62	24	95.83	119	1	100.00

Table B-4. Lightning Cluster Statistics for Flagstaff, Arizona. September 14, 1996 1104-1115 UTC. Image times: 1109-1115 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
62	7	28.57	93	10	60.00
65	9	77.78	94	1	100.00
66	3	66.67	95	2	50.00
68	16	18.75	96	2	100.00
69	2	50.00	97	17	47.06
70	3	33.33	98	1	100.00
72	4	100.00	99	10	100.00
73	1	100.00	100	2	0.00
74	22	54.55	101	7	71.43
75	4	100.00	102	1	0.00
76	8	100.00	103	2	50.00
77	15	100.00	104	17	70.59
78	8	75.00	105	3	66.67
79	6	83.33	106	3	66.67
80	20	30.00	107	4	25.00
81	11	90.91	108	2	100.00
82	8	37.50	109	4	25.00
83	4	0.00	110	1	100.00
84	1	100.00	111	1	0.00
85	5	100.00	112	1	0.00
86	5	60.00	113	1	100.00
87	13	46.15	114	1	100.00
88	1	100.00	115	3	66.67
90	7	85.71	116	1	100.00
91	1	100.00	117	1	100.00
92	6	83.33	118	1	100.00

Table B-5. Lightning Cluster Statistics for Flagstaff, Arizona. September 14, 1996 1116-1127 UTC. Image times: 1121-1127 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
92	1	100.00	116	8	100.00
93	5	100.00	117	4	100.00
94	1	100.00	118	7	100.00
95	4	100.00	119	16	87.50
96	4	100.00	120	3	100.00
97	20	100.00	121	2	50.00
98	1	100.00	122	15	100.00
99	8	50.00	123	3	100.00
100	2	100.00	124	6	50.00
101	13	100.00	125	4	25.00
102	3	100.00	126	5	60.00
103	1	100.00	127	12	100.00
104	10	100.00	128	2	0.00
105	1	100.00	129	2	100.00
106	4	100.00	130	11	100.00
107	1	0.00	131	1	0.00
108	1	100.00	132	2	100.00
109	1	0.00	133	1	0.00
110	12	100.00	134	1	100.00
111	10	60.00	135	2	0.00
112	4	0.00	136	1	100.00
113	1	100.00	137	1	100.00
114	1	100.00	138	2	100.00
115	6	66.67			

Table B-6. Lightning Cluster Statistics for Flagstaff, Arizona. September 14, 1996 1128-1138 UTC. Image times: 1133-1138 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
122	1	100.00	143	3	66.67
123	1	100.00	144	1	100.00
124	3	0.00	145	10	100.00
126	3	66.67	146	4	75.00
127	12	100.00	147	4	100.00
129	22	100.00	148	3	100.00
130	17	100.00	149	1	100.00
131	4	100.00	150	17	100.00
132	2	100.00	151	2	50.00
133	13	100.00	152	1	100.00
134	1	100.00	153	2	100.00
135	3	33.33	154	4	100.00
136	5	100.00	155	13	100.00
137	1	100.00	156	1	100.00
138	16	81.25	157	2	100.00
139	19	78.95	159	2	100.00
140	3	100.00	160	4	100.00
141	2	50.00	161	1	100.00
142	1	0.00	162	1	100.00

Table B-7. Lightning Cluster Statistics for Flagstaff, Arizona. September 14, 1996 1139-1150 UTC. Image times: 1144-1150 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
139	3	33.33	167	10	100.00
140	3	100.00	168	2	0.00
143	6	100.00	169	6	100.00
144	1	0.00	170	7	100.00
145	3	100.00	171	2	100.00
146	2	0.00	172	1	100.00
147	1	100.00	174	3	100.00
150	9	100.00	175	4	100.00
152	4	100.00	176	1	0.00
153	12	100.00	177	5	100.00
154	17	100.00	178	1	100.00
155	11	90.91	179	6	83.33
156	2	0.00	180	1	100.00
157	2	100.00	181	4	75.00
159	8	100.00	182	3	66.67
160	11	90.91	183	4	100.00
162	12	83.33	186	1	100.00
164	14	100.00	187	1	100.00
165	7	28.57	190	1	100.00

Appendix C. Lightning Statistics for Oklahoma City OK.

Appendix C contains lightning cluster statistics for Oklahoma City, Oklahoma for July 10,1999 from 0105-0215 UTC. The lightning cluster statistics are for eight radar images that occur over the following time period: 0100-0215 UTC.

Table C-1. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0100-0110 UTC. Image times: 0105-0110 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	277	92.42	14	22	54.55
2	130	100.00	15	7	100.00
3	49	97.96	16	5	100.00
4	86	93.02	17	2	50.00
5	59	91.53	18	3	33.33
6	46	89.13	19	5	100.00
7	21	76.19	20	3	100.00
8	43	97.67	21	1	100.00
9	23	100.00	22	2	100.00
10	12	100.00	23	1	100.00
11	14	92.86	24	2	50.00
12	9	100.00	25	1	100.00
13	4	50.00	26	1	100.00

Table C-2. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0111-0120 UTC. Image times: 0115-0120 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	34	38.24	28	24	100.00
2	14	57.14	29	89	59.55
3	10	90.00	30	52	46.15
4	5	80.00	31	21	100.00
5	3	100.00	32	25	100.00
7	5	80.00	33	4	75.00
8	8	100.00	34	36	72.22
9	1	100.00	35	17	47.06
11	13	30.77	36	3	0.00
12	11	81.82	37	16	56.25
13	24	45.83	38	16	68.75
14	5	40.00	39	1	100.00
15	11	100.00	40	5	100.00
16	2	100.00	41	4	100.00
17	34	61.76	42	9	77.78
18	4	75.00	43	3	0.00
19	32	43.75	44	2	100.00
20	13	100.00	45	2	100.00
21	80	43.75	46	2	100.00
22	7	100.00	47	1	100.00
23	4	50.00	48	1	100.00
24	140	62.14	49	1	100.00
25	21	47.62	50	2	100.00
26	91	45.05	68	1	100.00
27	5	80.00			

Table C-3. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0121-0130 UTC. Image times: 0125-0130 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
26	24	87.50	50	41	100.00
27	13	84.62	52	36	91.67
28	30	90.00	53	90	86.67
29	33	87.88	54	6	100.00
30	32	96.88	55	1	100.00
31	22	81.82	56	16	100.00
32	10	100.00	57	13	84.62
33	44	88.64	58	9	88.89
34	43	97.67	59	18	94.44
35	37	91.89	60	1	100.00
36	40	95.00	61	32	53.13
37	24	83.33	62	2	100.00
38	26	53.85	63	25	100.00
39	12	100.00	64	24	91.67
40	6	100.00	65	2	100.00
41	21	100.00	66	3	100.00
42	24	95.83	67	17	100.00
43	10	20.00	68	1	100.00
44	7	100.00	69	8	100.00
45	79	93.67	70	1	100.00
46	60	98.33	71	1	0.00
47	24	87.50	72	3	100.00
48	25	88.00	73	1	0.00
49	1	100.00			

Table C-4. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0131-0140 UTC. Image times: 0135-0140 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
44	1	100.00	73	10	20.00
48	10	100.00	74	39	92.31
50	2	100.00	76	7	85.71
52	47	91.49	77	16	100.00
53	40	97.50	78	28	85.71
54	40	85.00	79	23	69.57
56	12	58.33	80	5	100.00
57	35	88.57	81	6	66.67
58	25	92.00	82	1	100.00
59	78	88.46	83	16	93.75
60	2	0.00	84	1	100.00
61	43	37.21	85	7	100.00
62	6	100.00	86	6	33.33
63	38	86.84	87	2	50.00
64	43	86.05	88	1	100.00
65	39	92.31	89	1	100.00
66	19	100.00	90	8	62.50
67	16	68.75	91	2	50.00
68	8	87.50	92	3	100.00
69	7	100.00	93	1	100.00
70	37	100.00	94	1	100.00
71	7	0.00	95	5	0.00
72	27	100.00			

Table C-5. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0141-0150 UTC. Image times: 0145-0150 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
72	2	100.00	97	17	82.35
73	2	50.00	98	14	64.29
74	29	68.97	99	3	100.00
76	13	92.31	100	26	57.69
77	29	79.31	101	8	100.00
78	55	74.55	102	9	88.89
79	58	79.31	103	4	50.00
80	5	100.00	104	1	100.00
81	21	23.81	105	3	66.67
82	37	62.16	106	3	66.67
83	37	54.05	107	3	100.00
85	8	62.50	108	1	100.00
86	5	40.00	109	1	0.00
87	13	15.38	110	1	100.00
88	57	75.44	111	2	50.00
89	2	50.00	112	1	100.00
90	68	80.88	113	1	100.00
91	22	77.27	114	1	100.00
92	30	46.67	115	3	0.00
93	28	96.43	116	1	0.00
94	18	88.89	117	1	100.00
95	19	10.53	118	1	0.00
96	10	50.00			

Table C-6. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0151-0200 UTC. Image times: 0155-0200 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
91	5	80.00	119	3	100.00
92	3	100.00	120	2	100.00
93	8	75.00	121	17	94.12
94	3	100.00	122	13	100.00
96	33	90.91	123	6	100.00
97	10	80.00	124	30	96.67
98	10	50.00	125	4	100.00
99	34	97.06	126	13	100.00
100	32	81.25	128	2	100.00
101	6	33.33	129	2	100.00
102	34	94.12	130	10	70.00
103	11	100.00	131	18	72.22
104	22	81.82	132	1	100.00
105	31	100.00	133	3	100.00
106	7	85.71	134	2	100.00
107	28	85.71	135	1	100.00
108	66	95.45	136	4	75.00
109	84	94.05	137	2	100.00
110	38	100.00	138	7	57.14
111	17	100.00	139	2	50.00
112	2	100.00	140	2	50.00
113	45	86.67	141	1	100.00
114	9	100.00	142	1	100.00
115	17	70.59	143	1	100.00
116	45	97.78	144	1	100.00
117	8	87.50	145	1	100.00

Table C-7. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0201-0210 UTC. Image times: 0205-0210 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
114	3	100.00	147	10	80.00
115	1	100.00	148	18	77.78
116	23	91.30	149	15	93.33
117	9	77.78	150	1	100.00
119	2	100.00	151	3	66.67
121	22	90.91	152	13	69.23
122	31	77.42	153	3	66.67
123	68	92.65	154	24	91.67
124	33	93.94	155	5	60.00
125	23	100.00	156	9	88.89
126	7	100.00	157	13	53.85
128	9	88.89	158	4	100.00
129	40	52.50	159	7	100.00
130	29	93.10	161	2	100.00
131	44	90.91	162	1	100.00
132	40	85.00	163	1	100.00
133	34	91.18	164	2	100.00
136	18	100.00	165	10	30.00
137	14	100.00	166	3	100.00
138	24	50.00	168	1	100.00
140	1	100.00	169	2	50.00
141	7	100.00	170	2	100.00
142	33	93.94	171	1	100.00
143	29	86.21	172	1	0.00
144	19	89.47	174	1	0.00
145	51	80.39	175	3	66.67
146	4	75.00	176	2	100.00

Table C-8. Lightning Cluster Statistics for Oklahoma City Oklahoma. July 10, 1999 0211-0215 UTC. Image time: 0215 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
142	12	91.67	162	2	100.00
143	9	100.00	163	7	85.71
144	19	94.74	164	2	100.00
145	16	93.75	165	5	80.00
146	6	16.67	166	2	100.00
147	8	50.00	168	1	100.00
148	15	86.67	169	1	0.00
149	2	50.00	170	16	100.00
150	1	100.00	171	2	50.00
151	6	16.67	174	1	100.00
152	45	88.89	175	23	95.65
153	10	60.00	176	1	0.00
154	21	95.24	178	2	100.00
155	12	58.33	179	3	0.00
156	17	100.00	180	1	0.00
157	20	85.00	182	1	0.00
158	1	100.00	183	2	50.00
159	9	100.00	184	2	100.00

Appendix D. Lightning Statistics for Eglin AFB, FL.

Appendix D contains lightning cluster statistics for Eglin AFB, Florida for July 6-7,1996 from 2050-0015 UTC. The lightning cluster statistics are for 16 radar images that occur over the following time period: 2045-0015 UTC.

Table D-1. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2044-2056 UTC. Image times: 2050-2056 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	56	53.57	11	1	0.00
2	42	9.52	12	3	100.00
3	12	91.67	13	1	100.00
4	12	8.33	14	1	100.00
5	10	20.00	15	1	0.00
6	11	100.00	16	1	100.00
7	1	0.00	17	1	100.00
8	6	83.33	18	1	0.00
9	2	100.00	19	3	33.33
10	1	100.00	20	1	100.00

Table D-2. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2057-2108 UTC. Image times: 2102-2105 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
5	1	0.00	22	5	100.00
6	15	100.00	23	4	0.00
7	1	0.00	24	41	100.00
8	1	0.00	25	10	0.00
9	4	100.00	26	3	0.00
15	2	0.00	28	3	0.00
18	15	6.67	29	1	100.00
19	3	0.00	30	1	100.00
20	2	50.00			

Table D-3. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2109-2119 UTC. Image times: 2113-2119 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
23	2	50.00	34	1	100.00
24	7	100.00	35	1	0.00
29	2	100.00	36	1	100.00
30	8	100.00	37	1	100.00
33	19	100.00	40	1	100.00

Table D-4. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2120-2131 UTC. Image times: 2125-2131 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
33	22	77.27	39	1	100.00
34	1	0.00	40	1	100.00
35	4	25.00	41	4	0.00
36	2	50.00	42	4	75.00
37	7	100.00	43	2	0.00
38	21	95.24			

Table D-5. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2132-2143 UTC. Image times: 2137-2143 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
39	1	100.00	48	2	100.00
40	9	100.00	49	2	0.00
41	12	0.00	50	1	0.00
42	4	100.00	51	1	0.00
43	5	0.00	52	1	100.00
44	5	100.00	53	3	66.67
45	26	100.00	54	6	0.00
46	3	100.00	55	2	100.00
47	1	100.00			

Table D-6. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2144-2154 UTC. Image times: 2149-2154 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
45	7	28.57	56	10	0.00
46	3	66.67	57	7	57.14
49	1	100.00	58	2	0.00
50	1	0.00	59	2	0.00
51	1	100.00	60	3	33.33
52	3	33.33	61	3	100.00
53	8	37.50	62	1	100.00
54	14	28.57	64	1	100.00
55	5	100.00			

Table D-7. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2155-2206 UTC. Image times: 2200-2206 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
56	6	33.33	66	1	100.00
57	2	100.00	67	1	0.00
58	2	0.00	68	3	0.00
60	6	0.00	69	6	100.00
61	5	0.00	70	2	0.00
62	7	0.00	71	2	50.00
64	1	100.00	72	1	100.00
65	13	100.00			

Table D-8. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2207-2218 UTC. Image times: 2212-2218 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
65	4	100.00	75	7	71.43
67	3	0.00	76	5	0.00
68	2	0.00	77	1	100.00
69	7	28.57	78	1	100.00
70	6	0.00	79	1	0.00
72	2	0.00	81	1	0.00
73	11	81.82	82	1	0.00
74	30	0.00			

Table D-9. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2219-2230 UTC. Image times: 2224-2230 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
73	2	100.00	84	3	100.00
74	2	50.00	85	1	100.00
75	11	100.00	86	12	100.00
76	2	0.00	88	7	100.00
77	1	100.00	89	12	25.00
78	1	100.00	90	3	100.00
79	1	100.00	91	1	0.00
82	7	100.00	92	1	100.00
83	1	100.00			

Table D-10. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2231-2241 UTC. Image times: 2235-2241 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
86	9	88.89	94	12	91.67
88	10	60.00	95	1	100.00
89	17	11.76	96	4	100.00
90	2	0.00	97	5	80.00
92	1	0.00	98	2	100.00
93	7	85.71	99	18	0.00

Table D-11. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2242-2253 UTC. Image times: 2247-2253 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
94	5	100.00	100	1	100.00
95	2	50.00	101	2	0.00
96	2	50.00	102	11	100.00
97	10	100.00	104	34	91.18
98	3	100.00	105	2	0.00
99	15	0.00	106	3	100.00

Table D-12. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2254-2305 UTC. Image times: 2259-2305 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud	Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
102	4	50.00	108	19	100.00
104	21	95.24	109	1	100.00
105	5	20.00	110	3	0.00
106	7	85.71			

Table D-13. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2306-2316 UTC. Image times: 2311-2316 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
108	12	91.67
109	1	0.00
111	1	0.00

Table D-14. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2317-2328 UTC. Image times: 2322-2328 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
111	1	0.00
112	11	81.82
113	1	100.00
114	5	80.00
115	2	0.00

Table D-15. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2329-2340 UTC. Image times: 2334-2340 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
114	2	50.00
115	2	0.00
117	10	30.00

Table D-16. Lightning Cluster Statistics for Eglin AFB, Florida. July 6, 1996 2341-2352 UTC. Image times: 2346-2352 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
118	2	100.00

Appendix E. Lightning Statistics Melborne, FL.

Appendix E contains lightning cluster statistics for Melbourne, Florida for August 13, 1996 from 2022-2341 UTC. The lightning cluster statistics are for 21 radar images that occur over the following time period: 2016-2341 UTC.

Table E-1. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2017-2027 UTC. Image times: 2022-2027 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	62	80.65
2	8	100.00
3	26	100.00
4	14	100.00
5	4	100.00
6	4	100.00
7	14	100.00
8	2	100.00
9	3	100.00
10	4	75.00
12	2	100.00
13	1	100.00
14	1	0.00
15	1	100.00
16	1	100.00
25	1	100.00

Table E-2. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2028-2037 UTC. Image times: 2032-2037 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
1	62	82.26
2	8	100.00
3	26	11.54
4	14	57.14
5	4	0.00
6	1	0.00
7	14	100.00
8	2	100.00
9	3	66.67
10	4	75.00
12	2	50.00
13	1	100.00
14	1	0.00
15	1	100.00
16	1	100.00
25	1	0.00

Table E-3. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2038-2046 UTC. Image times: 2042-2046 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
17	20	30.00
18	1	100.00
19	42	92.86
20	8	75.00
21	10	90.00
22	9	88.89
24	1	100.00
25	2	0.00
26	1	100.00
27	55	27.27
28	4	0.00
29	1	100.00
30	2	0.00
31	49	79.59
32	3	66.67
33	7	57.14
34	7	100.00
35	3	100.00
36	1	100.00
37	1	100.00

Table E-4. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2047-2056 UTC. Image times: 2051-2056 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
27	44	9.09
29	1	0.00
30	2	100.00
31	79	26.58
33	13	0.00
34	20	30.00
35	8	37.50
38	3	0.00
39	3	33.33
40	26	26.92
41	6	100.00
42	3	0.00
44	5	100.00
45	1	0.00
46	1	0.00

Table E-5. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2057-2106 UTC. Image times: 2101-2106 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
36	1	100.00
39	16	6.25
40	17	5.88
41	7	100.00
42	1	0.00
44	6	83.33
45	4	0.00
46	71	32.39
47	3	0.00
48	3	66.67
49	4	0.00
50	2	100.00
51	2	0.00
52	3	0.00

Table E-6. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2107-2116 UTC. Image times: 2111-2116 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
45	1	100.00
46	15	26.67
47	4	50.00
48	15	40.00
49	12	75.00
50	6	100.00
51	1	100.00
52	10	70.00
53	5	100.00
54	8	100.00
55	26	69.23
56	8	0.00
57	1	100.00
58	3	0.00
59	1	0.00
60	3	100.00
61	1	0.00
62	1	100.00

Table E-7. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2117-2126 UTC. Image times: 2121-2126 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
52	1	0.00
54	8	100.00
55	30	16.67
56	8	0.00
57	4	75.00
58	2	0.00
60	29	89.66
61	9	0.00
62	6	66.67
63	1	0.00
64	8	75.00
65	4	0.00
66	11	100.00
67	3	100.00
68	1	0.00
69	2	0.00
70	2	0.00
71	1	100.00

Table E-8. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2127-2136 UTC. Image times: 2131-2136 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
62	2	50.00
64	7	85.71
66	31	100.00
67	16	100.00
69	5	0.00
70	6	16.67
71	49	95.92
72	2	100.00
73	7	57.14
74	17	100.00
75	3	100.00
76	1	100.00
77	4	100.00

Table E-9. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2137-2146 UTC. Image times: 2141-2146 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
71	4	75.00
72	5	80.00
73	3	66.67
74	13	92.31
75	25	100.00
76	1	100.00
77	13	100.00
78	5	40.00
79	2	50.00
80	1	100.00
81	2	0.00
82	16	81.25
83	2	100.00
84	5	60.00
85	41	73.17
86	3	100.00

Table E-10. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2147-2156 UTC. Image times: 2151-2156 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
77	2	100.00
78	1	100.00
79	1	100.00
80	5	80.00
82	21	61.90
83	2	50.00
84	1	0.00
85	22	40.91
86	7	71.43
89	3	100.00
90	20	45.00
91	1	100.00
93	1	0.00
101	1	0.00

Table E-11. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2157-2206 UTC. Image times: 2201-2206 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
89	3	100.00
90	61	100.00
91	2	100.00
93	15	100.00
94	1	0.00
95	10	100.00
96	3	0.00
97	1	0.00
98	1	0.00
99	2	100.00

Table E-12. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2207-2216 UTC. Image times: 2211-2216 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
93	2	100.00
94	1	100.00
95	42	97.62
96	10	100.00
97	2	100.00
99	33	100.00
100	3	100.00
101	14	100.00
102	2	100.00
103	2	100.00
104	1	100.00
105	3	100.00
106	1	100.00

Table E-13. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2217-2226 UTC. Image times: 2221-2226 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
99	6	100.00
100	6	100.00
101	27	100.00
102	3	100.00
103	49	100.00
105	33	0.00
107	1	0.00
108	1	0.00
109	5	80.00
110	4	0.00
111	6	100.00
112	15	100.00
113	2	100.00

Table E-14. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2227-2236 UTC. Image times: 2231-2236 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
105	1	0.00
109	1	100.00
110	2	0.00
111	5	60.00
112	15	53.33
113	6	83.33
114	30	96.67
115	8	75.00
116	32	0.00
117	11	0.00
118	1	100.00
119	1	0.00
120	2	100.00
121	3	33.33

Table E-15. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2237-2246 UTC. Image times: 2241-2246 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
114	5	20.00
115	3	66.67
116	8	0.00
117	1	0.00
118	6	100.00
119	5	0.00
120	1	0.00
121	8	25.00
122	11	0.00
123	23	26.09
124	10	80.00
125	39	64.10
126	1	100.00
127	3	0.00
128	8	12.50
129	3	66.67
130	1	100.00
131	1	100.00
132	1	0.00

Table E-16. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2247-2256 UTC. Image times: 2251-2256 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
120	1	0.00
123	19	100.00
124	3	100.00
125	13	69.23
127	1	0.00
128	24	0.00
129	9	44.44
130	2	0.00
131	8	0.00
133	30	0.00
134	20	0.00
135	12	25.00
136	2	0.00
137	16	100.00
138	2	0.00
139	11	45.45
140	22	4.55
141	1	100.00
142	3	0.00

Table E-17. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2257-2306 UTC. Image times: 2301-2306 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
133	13	0.00
134	8	0.00
135	2	100.00
137	8	100.00
139	11	100.00
140	12	16.67
141	28	17.86
142	60	1.67
143	27	0.00
145	5	0.00
146	4	100.00
147	10	10.00
148	7	100.00
149	2	0.00
150	2	100.00
151	1	100.00
152	1	100.00
163	1	0.00

Table E-18. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2307-2316 UTC. Image times: 2311-2316 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
142	14	0.00
143	40	2.50
145	7	14.29
146	4	100.00
147	26	0.00
148	13	100.00
149	1	0.00
151	2	100.00
152	3	100.00
154	42	0.00
155	2	0.00
156	2	50.00
158	1	100.00
159	24	4.17
160	1	0.00
162	2	0.00
163	2	0.00

Table E-19. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2317-2326 UTC. Image times: 2321-2326 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
152	3	100.00
154	22	9.09
155	8	0.00
156	38	0.00
159	36	2.78
160	20	5.00
162	8	0.00
163	8	12.50
164	6	100.00
165	1	0.00
166	1	100.00
167	2	0.00
168	2	0.00
169	1	0.00

Table E-20. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2327-2336 UTC. Image times: 2331-2336 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
166	24	12.50
167	55	0.00
168	8	0.00
169	8	0.00
170	3	66.67
171	1	0.00
172	3	0.00
174	1	0.00
175	1	0.00

Table E-21. Lightning Cluster Statistics for Melbourne, Florida. August 13, 1996 2337-2346 UTC. Image times: 2341-2346 UTC.

Cluster Number	# of Flashes in Cluster	% of Flashes in Cloud
168	8	100.00
169	1	100.00
171	4	100.00
172	6	100.00
174	8	100.00
176	5	100.00
177	2	100.00
179	1	100.00

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Vita

First Lieutenant Rhonda B. Scott, was born in Washington, Georgia. She graduated from Biloxi High School, Biloxi, Mississippi in 1992. From high school she went on to attend the United States Naval Academy Preparatory School and entered the United States Naval Academy (USNA) Class of 1997 during the summer of '93. She graduated from USNA with a Bachelor of Science degree in Oceanography and received a commission in the United States Air Force in May 1997.

After attending the Weather Officer Course at Keesler AFB, Mississippi Lieutenant Scott's first assignment was Seymour Johnson AFB in Goldsboro, North Carolina where she was the Wing Weather Officer. While stationed at Seymour Johnson AFB she was deployed to Howard AFB, Panama for ninety days.

In August of 1999, she entered the graduate meteorology program in the School of Engineering at the Air Force Institute of Technology. During her time at AFIT she married her college sweetheart Following graduation, Lieutenant Scott will be assigned to the Radar Operation Center located in Norman, Oklahoma.

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14. ABSTRACT

The most recent research conducted at the Air Force Institute of Technology involved studying a large volume of lightning data without coupling radar imagery (Parsons 2000). Parsons finding could not be acted on because no individual storms were studied. The primary goal of this research is to determine whether the techniques used by Parsons can be applied to storms by examining the radar imagery and lightning data. This research used the methodology applied to lightning data by Parsons and radar imagery to determine whether the location of lightning clusters were located near storms. A composite reflectivity radar image was generated and the lightning data for the corresponding time was plotted to determine if lightning clusters corresponded to storm coverage area. After a visual analysis of the radar and lightning cluster plots was conducted, the percentage of lightning clusters found in each radar image was calculated. Caution needs to be applied when calculating the distance to the flashes isolated from nearby clusters since the clusters were found to be near the edge of the storms studied and not under the convective core of the storm. This research was successful in proving that the DBSF method may be applied, however more research must be done to determine what location of the storm provides the best distance criteria measurements.

15. SUBJECT TERMS

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